

STUDIES OF PREMIXED LAMINAR AND TURBULENT FLAMES AT MICROGRAVITY

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INTRODUCTION

Several topics relating to premixed flame behavior at reduced gravity have been studied. These topics include: (1) flame balls; (2) flame structure and stability at low Lewis number; (3) experimental simulation of buoyancy effects in premixed flames using aqueous autocatalytic reactions; and (4) premixed flame propagation in Hele-Shaw cells. Because of space limitations, only topic (1) is discussed here, emphasizing results from experiments on the recent STS-107 Space Shuttle mission, along with numerical modeling efforts.

STRUCTURE OF FLAME BALLS AT LOW LEWIS-NUMBER (SOFBALL) EXPERIMENT

The objective of the SOFBALL space flight experiment was to study weakly burning flames in hydrogen-oxygen-inert and methane-oxygen-inert mixtures in a configuration called "flame balls" that were originally predicted by Zeldovich in 1944 but not seen experimentally until over 40 years later in short-duration drop tower experiments [1]. Because flame balls are steady, convection-free, spherically symmetric and occur in fuels with simple chemistry, they represent the simplest possible interaction of chemistry and transport in flames. In this sense flame balls bear a similar relationship to combustion research that the fruit fly does to genetics research.

On STS-107 a total of 39 tests were performed in 15 different mixtures, resulting in a total of 55 flame balls, of which 33 were named by the crew. Most tests (by design) produced only 1 flame ball, though one test intentionally designed to produce a large number of flame balls resulted in 9 balls. The total burn time for all flames was 6 $\frac{1}{4}$ hours. Since flame balls are extremely sensitive to gravitational acceleration, all tests were conducted during orbiter free drift periods. The quality of the microgravity was found to be excellent, averaging less than 1 micro-g for most tests. Over half of the science data was downlinked during the mission, resulting in minimal loss of science despite the loss of Columbia and its crew. Among the accomplishments of the experiment were

- The weakest flames ever burned, either in space or on the ground. The weakest flame balls produced about 0.5 watts of thermal power. By comparison a birthday candle produces about 50 watts of thermal power.
- The leanest flames ever burned, either in space or on the ground. The leanest hydrogen-air test points contained 3.2 mole percent H₂ in air (equivalence ratio < 0.079).
- The longest-lived flame ever burned in space (81 minutes)

Several totally new results were found, including

- Oscillating flame balls that were predicted theoretically [2] but heretofore never observed experimentally (Fig. 1). It is not been established whether the mechanism outlined in [2] is responsible for the observed oscillations.
- For some tests, particularly in methane-oxygen-sulfur hexafluoride mixtures, flame ball drift not related to gravitational disturbances nor interactions with other balls or walls. This was a completely unexpected and as yet unexplained result.

Several issues not resolved during the previous space flight experiments on STS-83 and STS-94 in 1997 [3] were addressed by experiments on STS-107:

- *Can flame balls last much longer than the 500 sec maximum test time on STS-83 and STS-94 if free drift (no thruster firings) can be maintained for the entire test?* Answer: not usually - some type of flame ball motion, not related to microgravity disturbances, causes flame balls to drift to walls within \approx 1500 seconds. The only exception to this was the

very last test in which 9 flame balls formed initially (Fig. 2) and extinguished one by one until only one (name “Kelly” by the crew) remained. Unexpectedly, Kelly survived 81 minutes, seemingly immune to drift, until it was intentionally extinguished due to operational limitations (it was still burning at the time). The mechanism responsible for the drift of isolated flame balls has not yet been identified, though some mechanisms have been proposed [4]. The shorter-than-expected test times on most tests meant enough time for multiple reburns of each mixture within the flight timeline.

- *Can oscillating flame balls be observed in long-duration, free-drift conditions?* Answer: Probably, but it is still necessary to determine if flame ball motion rather than inherent oscillations of stationary flame balls may have caused the observed oscillations).
- *Are higher Lewis number flame balls (e.g. $H_2-O_2-He-CO_2$, $Le \approx 0.8$) more likely to oscillate, as predicted theoretically [2]?* Answer: No. These flames were extremely stable (Fig. 3).
- *Do the flame balls using methane ($CH_4-O_2-SF_6$ mixtures) behave differently from those in hydrogen fuel (e.g. $H_2-O_2-SF_6$ mixtures)?* Answer: Yes. They frequently drifted in corkscrew patterns, though again the mechanism responsible for this drift is not clear.

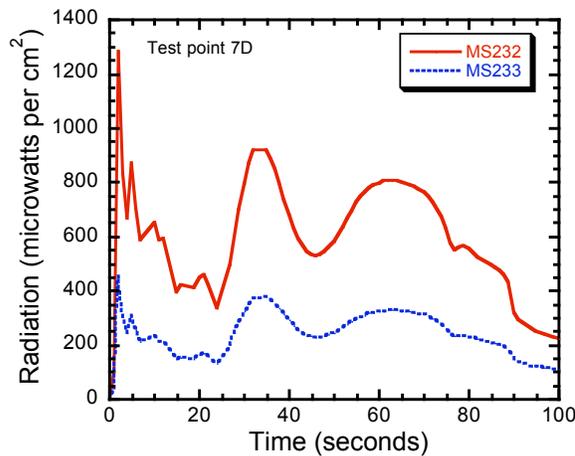


Figure 1. Signals from two different radiometers showing flame ball oscillations. Mixture: 9.9% CH_4 – 19.8% O_2 – 70.3% SF_6 at 1 atm. This test produced 1 flame ball.

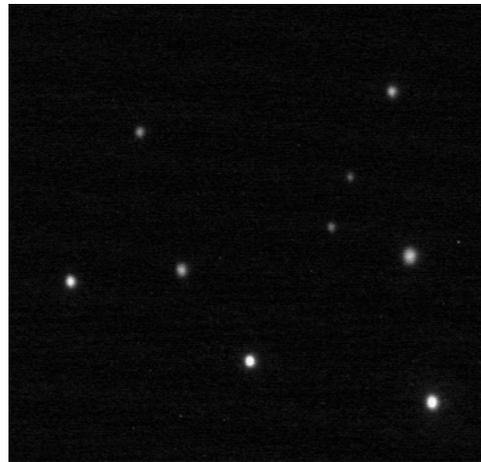


Figure 2. Image of flame balls in a 7.5% CH_4 – 15% O_2 – 77.5% SF_6 mixture at 3 atm.

NUMERICAL MODELING OF FLAME BALLS

Despite their simplicity, flame balls present a number of interesting challenges to the computationalist. In particular, prior computations comparing results obtained assuming optically thin vs. optically opaque (no transmission) CO_2 radiation suggest that reabsorption of emitted radiation is probably a dominant effect in flame ball mixtures diluted with CO_2 . Consequently, an investigation of the effects of reabsorption of emitted radiation on flame balls was conducted using a numerical code [5] with detailed chemical, transport, and radiative emission-absorption models. A Statistical Narrow Band – Discrete Ordinates method was used to model radiative transport [6]. The boundary conditions were ambient temperature and composition at the outer boundary with a blackbody wall. Zero gradient and zero radiative flux conditions were enforced at $r = 0$.

The predicted flame radius (r^*), which is defined at the location of maximum volumetric heat release, and total radiative heat loss are plotted as a function of fuel-equivalence ratio (ϕ), for H_2 -air mixtures with and without reabsorption in Fig. 4. Consistent with theory [7], for this stable solution branch r^* increases with fuel concentration for both cases with and without reabsorption. It is observed that reabsorption of emitted radiation leads to larger flame ball sizes and extinction limits shifted toward weaker fuel concentrations than calculations using optically-thin radiation models. In addition, it is noteworthy that the total radiative loss is actually greater with

reabsorption. Figure 4 also shows comparisons between the numerical predictions and the space experimental results. The agreement between model and experiment is better with regard to flame radius, but worse with respect to radiative loss, when reabsorption (i.e. optically-thick radiation) effects are considered.

Figure 5 shows the predicted flame radius and total radiative heat loss as a function of fuel concentration for H_2 - O_2 - CO_2 mixtures with and without reabsorption, along with the space experimental results. In this case much stronger reabsorption effects can be anticipated because the diluent gas itself is strongly emitting/absorbing. In fact, the net radiative loss with reabsorption was only about 1/1000 that that would occur with the same temperature and species concentration profiles were the mixture optically thin. Similar to the H_2 -air mixtures (Fig. 4), Fig. 5 shows that the agreement between model and experiment is better with regard to flame radius when reabsorption effects are considered, although the agreement is somewhat worse than that for the H_2 -air mixtures. In addition, when reabsorption effects are considered, comparison with the experiments is more favorable with respect to the total heat loss, which is different from the case of the H_2 -air mixtures.

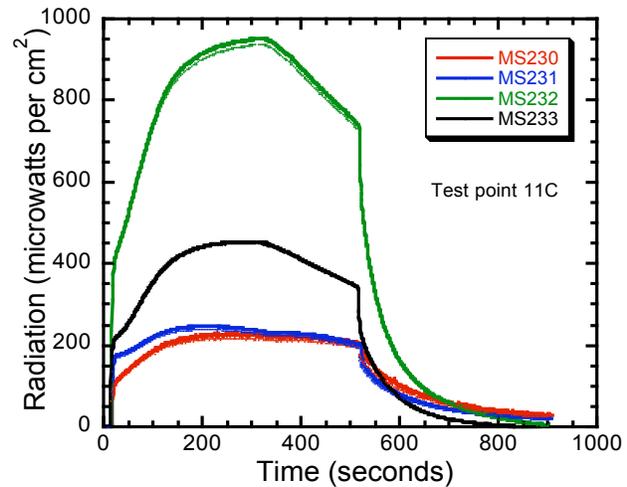


Figure 3. Signals from two different radiometers showing flame ball oscillations. Mixture: 9.9% CH_4 – 19.8% O_2 – 70.3% SF_6 at 1 atm. This test produced 1 flame ball.

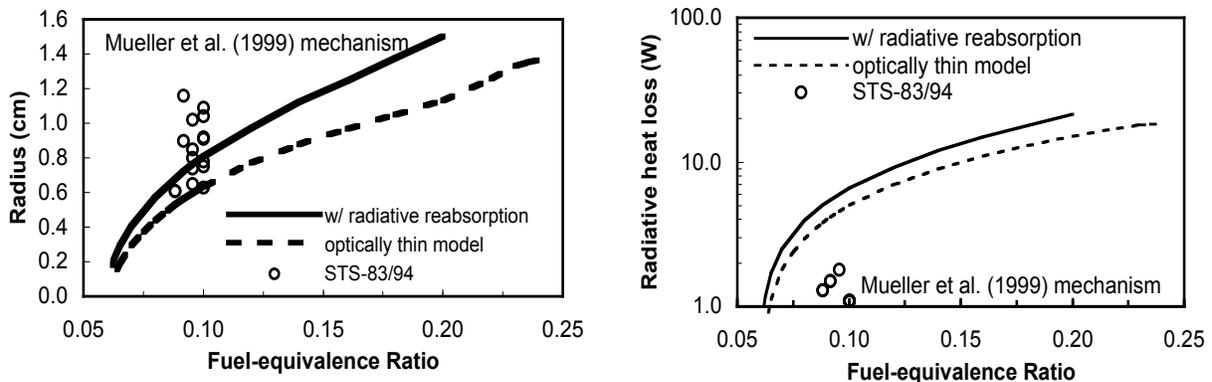


Figure 4. Predicted (lines) and measured (symbols) flame ball radius (left) and total heat loss (right) as a function of fuel-equivalence ratio for steady H_2 -air flame balls at 1 atm. Predictions based on the Mueller et al. (1999) mechanism and with Soret effects. Measurements from Space Shuttle missions STS-83 and STS-94.

Figure 6 (left) shows the predictions of flame ball radius as a function of fuel-equivalence ratio for the H_2 -air mixtures, using the GRI mechanism [8], with and without the Soret effect. As shown in the figure, the Soret effect is found to be significant; in particular, for the near-extinction limit conditions the predicted values of r^* with the Soret effect almost double those of r^* without the effect. This observation was somewhat expected because it has an effect similar to increasing the fuel concentration or decreasing the effective Lewis number. In order to evaluate the effect of different reaction mechanisms, the predictions of flame ball radius as a function of fuel-equivalence ratio for the H_2 -air mixtures are shown in Fig. 6 (right). For this comparison, the

Soret effect was included for both the cases. Considering the comparison of the predictions with the space experimental results in Fig. 1, although the Mueller *et al.* [9] mechanism provides a slightly better prediction with respect to flame radius, it does not with respect to total heat loss.

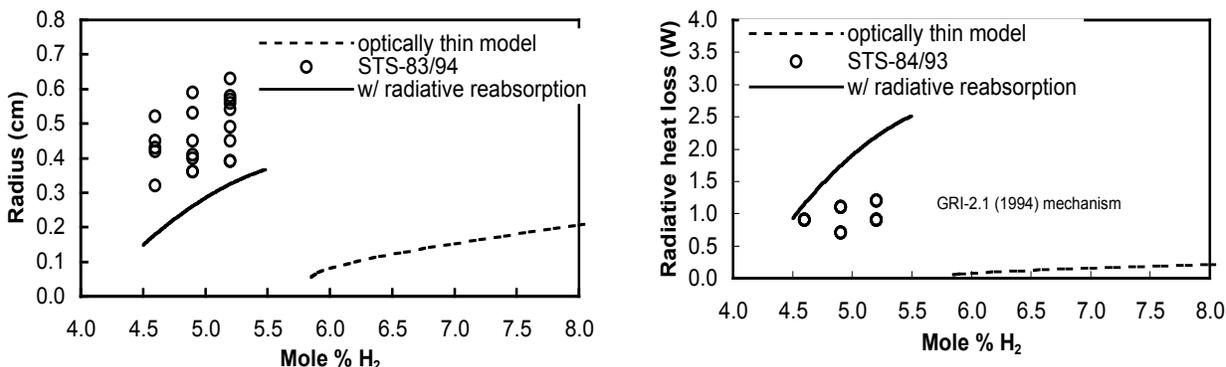


Figure 5. Predicted (lines) and measured (symbol) flame ball radius (left) and total heat loss (right) as a function of fuel concentration (%) for steady $H_2-O_2-CO_2$ flame balls of $\phi = 0.25$ at 1 atm. Measurements from Space Shuttle missions STS-83 and STS-94.

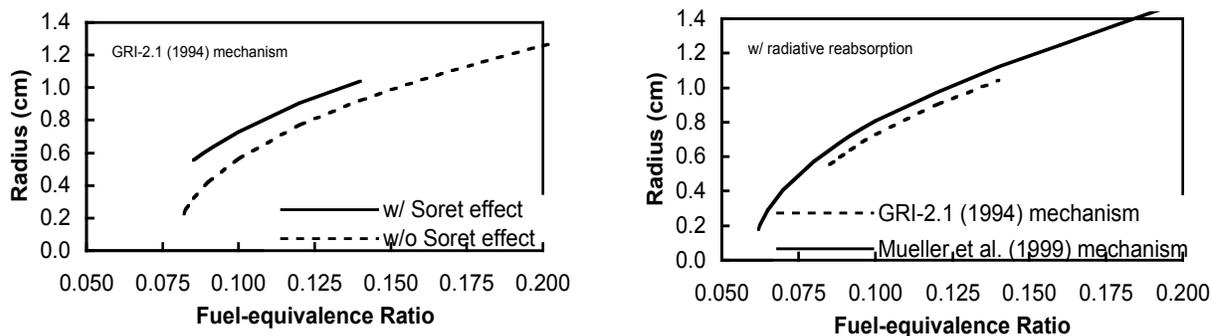


Figure 6. Left: predicted flame ball radius as a function of fuel-equivalence ratio for steady H_2 -air flame balls at 1 atm, with and without Soret effects. Right: predicted flame ball radius as a function of fuel-equivalence ratio for steady H_2 -air flame balls at 1 atm, with radiative reabsorption and Soret effects, comparing the Mueller *et al.* (1999) and GRI (Frenklach *et al.*, 1994) mechanisms.

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